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# Preliminary Analysis of Burnable Absorber Concepts for Seaborg Compact Molten Salt Reactor

Taesuk Oh [a], Eunhyug Lee [a], Youngbeom Son [b], and Yonghee Kim [a*]
[a] *Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*
[b] *Nuclear Engineering, Kyung Hee University, Gyeonggi-do, Republic of Korea*
[*] *Corresponding author: yongheekim@kaist.ac.kr*

## 1. Introduction

As the role and importance of nuclear energy for confronting fossil-fuel-driven global climate issues is being recognized, interest in developing advanced nuclear technology is also gaining attention including the molten salt reactor (MSR) concepts [1]. Unlike the conventional PWRs or fast reactors, the MSR utilizes the liquid-fuel salt to comprise the active core, which also serves the role of coolant.

To provide long-life operation without any online fuel treatment to procure proliferation resistance and minimize radioactive waste, most of the newly proposed MSR concepts are based on the fast-spectrum design [2]. Nevertheless, there still exist several startup companies that pursue the thermal spectrum-based MSR concepts including Seaborg Technologies' compact molten salt reactor (CMSR) [3].

The CMSR has a thermal power output of 250 MWth and is comprised of NaF-KF-$UF_4$ ternary fuel salt being encapsulated within a tube, surrounded by NaOH salt-based moderator. Since detailed information of CMSR, is not publicly accessible, proper improvisations have been made if necessary throughout this work.

For achieving long-life operation without online fuel treatment, it is essential for the system to attain enough initial excess reactivity. During operation, soluble boron can be applied as a means for maintaining criticality; however, it incurs safety concerns as it renders the moderator feedback to be positive. To circumvent such an issue, burnable absorber concepts has been envisaged, where its detailed configuration, applicability, and impact on the neutronics behaviour are investigated in this paper.

## 2. Seaborg CMSR Core Neutronics Design

Figure 1 depicts the overall layout of CMSR where its active core consists of 235 fuel channel tubes with an inner diameter of 10 cm. Each channel tube has an inner and outer Hastelloy-N annulus with a thickness of 0.1 cm that encircles 0.3 cm thickness of SS316 stainless steel. The composition of the fuel salt is assumed to be 45NaF-22.2KF-32.8$UF_4$ (mole %) with a uranium enrichment of 19.75 w/o. Note that such a composition corresponds to one of the eutectic conditions having a melting temperature of 808 K [4]. The active core has a diameter of 2.5 meters including a 5 cm thickness of Hastelloy-N annulus as a structural material, and its height is about 200 cm. The NaOH moderator fills the active core and same volume of fuel salts has been postulated for both active and inactive core region which has an outer radius of 137.32 cm. The material information for each component under temperature of 923.15 K is enumerated in Table 1.

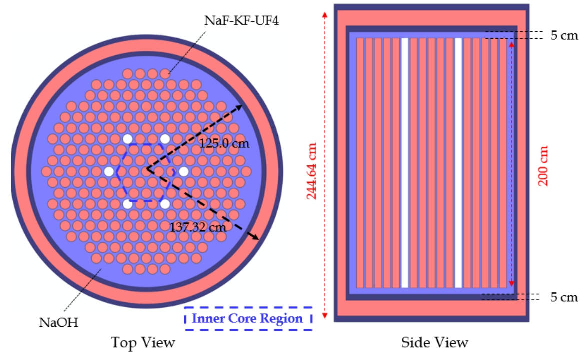


Figure 1. Overall layout of CMSR

Table 1. Material Composition for CMSR

| Components | Materials | Density (g/cc) |
|---|---|---|
| Fuel Salt | NaF-KF-$UF_4$ | 4.261 |
| Moderator Salt | NaOH | 1.6264 |
| Fuel tube (in/out) | Hastelloy-N | 8.86 |
| Fuel tube | SS316 | 8.00 |

*Evaluated at 923.15 K

## 3. Burnable Absorber Concepts

As aforementioned, it is necessary for the reactor to have enough initial excess reactivity to provide long-life operation without online fuel treatment. However, such a condition insinuates a stringent burden for controlling the excess reactivity during operation, i.e., depletion. A similar approach to that of the conventional PWRs may be considered, which utilizes the soluble boron [5]. However, the presence of a significant amount of soluble boron deteriorates the inherent safety since the moderator temperature coefficient (MTC) becomes more positive.

Hence, a different measure should be devised to control the excess reactivity during operation for CMSR whilst not undermining the safety feature. For such a purpose, burnable absorber (BA) concepts have been investigated, where the extent of reactivity control can be adjusted by varying the degree of self-shielding, i.e., change in geometry including width, thickness, etc.

To reduce the reactivity swing below about 1,000 pcm during depletion, both plate and rod type BAs which consist of natural $B_4C$ meat and either zircaloy or SS316-based cladding of 150 µm have been considered as shown in Fig. 2 and Table 2. Since the neutron absorption by B-10 produces $^7Li$ and $^4He$, cladding should be equipped with micro-holes for removal of gaseous $^4He$ to maintain structural integrity during operation. Further material compatibility-related issues will be investigated in a separate work, although usage of SS316 is expected to provide improved corrosion resistance than that of zircaloy cladding.

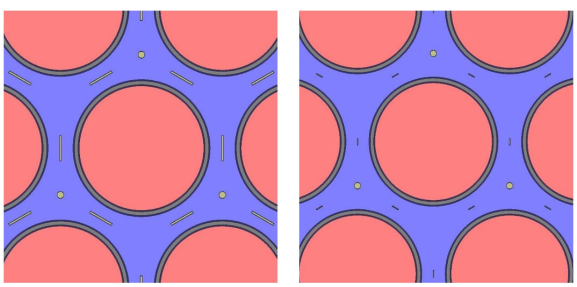


Figure 2. Burnable absorber configurations for inner and outer core of CMSR.

Table 2. Configuration of each burnable absorber

| Type | Geometry | Location |
|---|---|---|
| Rod-in | $r_{ROD}$ = 0.260 cm | Inner Core |
| Rod-out | $r_{ROD}$ = 0.271 cm | Outer Core |
| Plate-in | Width = 0.12 cm<br>Length = 1.980 cm | Inner Core |
| Plate-out | Width = 0.05 cm<br>Length = 0.540 cm | Outer Core |

### 4. Numerical Results

To examine the applicability of the proposed burnable absorber concepts for CMSR, depletion calculation has been performed using the Serpent Version 2.131 continuous energy Monte Carlo transport program [6] and ENDF/B-VII.1 data library. Figure 3 compares the evolution of excess reactivity during depletion and plainly depicts the mitigation of reactivity swing below 1,000 pcm through the usage of BAs regardless of the cladding material, where the uncertainty of calculated

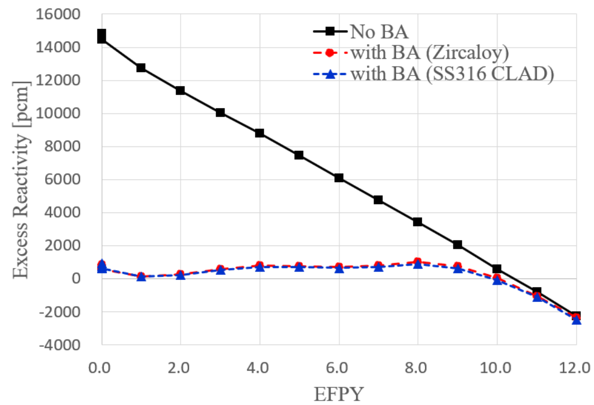


Figure 3. Evolution of excess reactivity during depletion.

reactivity is about 15 pcm for all cases. The estimated discharge burnup for the reference case, i.e., no BA, was about 52.27 GWD/MTU whereas the discharge burnups for including the BAs were about 50.82 GWD/MTU and 49.73 GWD/MTU for zircaloy and SS316 cases respectively. Considering the advantages of alleviating the necessity of including soluble boron, e.g., less positive MTC, such decrement in the discharge burnups is regarded acceptable.

In order to scrutinize possible favourable/adverse neutronics effects caused by the BA concepts, radial flux profile and MTC values have been calculated. For evaluation of temperature dependent NaOH density value, the following equation has been implemented [7]:

$$\rho_{NaOH}\left[\frac{g}{cc}\right] = 2.068 - 0.4784 \times 10^{-3}T\ [K]. \quad (1)$$

Figure 4 demonstrates the normalized radial flux distribution within the active core evaluated at BOL (0.00 GWD/MTU), MOL (25.06 GWD/MTU), and EOL (50.12 GWD/MTU) conditions for reference (no BA) and with BA (zircaloy cladding) cases. It could be seen that the change in the radial flux profile is marginal for the reference case, whereas noticeable variation exists for the case including the BAs. Especially, a strong flux suppression occurs for the inner core region at BOL, mainly due to the presence of strong absorbers. However, since the radial flux profile at EOL condition does not exhibit conspicuous difference, it is expected that no additional safety concern pertaining to localized power peaking issue would occur.

Figure 5 compares the normalized spectrum at BOL and EOL conditions for including/excluding the BAs. One could observe a strong suppression in the thermal energy region, i.e., spectrum hardening when BAs are considered for BOL conditions. In addition, regardless of the inclusion of burnable absorber concepts, the spectrum near ~ 1.0 eV reduces at EOL conditions, which corresponds to the build-up of plutonium.

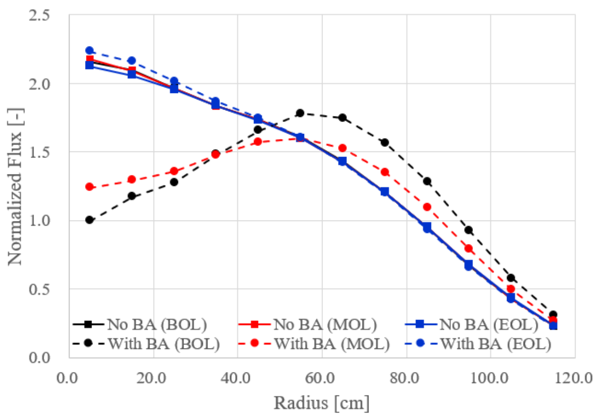


Figure 4. Normalized radial flux profile for reference (no BA) and having BA cases.

The disparities in the neutron spectrum at each condition will manifest as a change in the moderator temperature coefficient (MTC) value. Since the reactor of interest operates based on (epi-)thermal energy region, suppression of neutron spectrum in the thermal region would incur less positive MTC values. Note that it is the change of MTC values due to the presence of BAs that is the main interest of this work, where an accurate estimation of MTC values and analysis of shutdown margin requires further detailed information of CMSR.

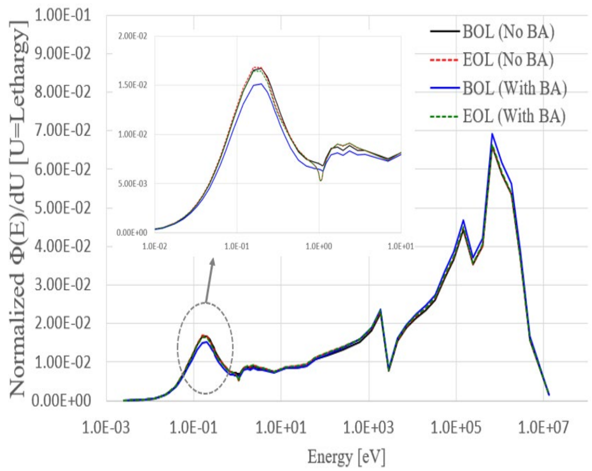


Figure 5. Normalized neutron energy spectrums for BOL/EOL conditions.

Tables 3 and 4 enumerate the calculated MTC values at BOL and EOL conditions depending on the presence of BAs for various temperature ranges. It could be seen that MTC values tend to decrease with an increase in the temperature, which could be explained through weakening of self-shielding like effect between the moderator atoms as density reduces.

For BOL conditions without burnable absorbers, positive MTC values greater than unity can be seen, which insinuates an over-moderated situation. It is noteworthy to mention that the implementation of soluble boron for such a condition will further increase the MTC values, posing a serious safety concern.

When BAs are included, the evaluated MTC values at the BOL condition become relatively smaller than the case for excluding the BAs. Such a reduction stems from the substitution of moderator volume with an absorber which hardens the spectrum that weakens the extent of over-moderation, resulting in more negative MTC values. In addition, as the burnup increases, a buildup of plutonium isotopes from U238 conversion results in localized spectrum suppression. Hence, the MTC values evaluated at the EOL condition for not having BAs will

Table 3. MTC values for CMSR w/o BA

| BOL Condition | | |
|---|---|---|
| Temperature Range [K] | MTC [pcm/K] | Uncertainty [pcm/K] |
| 823.15~873.15 | 1.66 | 0.05 |
| 873.15~923.15 | 1.22 | 0.05 |
| 923.15~973.15 | 0.88 | 0.05 |
| 973.15~1023.15 | 0.60 | 0.05 |
| **EOL Condition** | | |
| Temperature Range [K] | MTC [pcm/K] | Uncertainty [pcm/K] |
| 823.15~873.15 | 1.62 | 0.06 |
| 873.15~923.15 | 1.05 | 0.05 |
| 923.15~973.15 | 0.49 | 0.05 |
| 973.15~1023.15 | 0.16 | 0.05 |

Table 4. MTC values for CMSR with BA

| BOL Condition | | |
|---|---|---|
| Temperature Range [K] | MTC [pcm/K] | Uncertainty [pcm/K] |
| 823.15~873.15 | 0.99 | 0.07 |
| 873.15~923.15 | 0.54 | 0.06 |
| 923.15~973.15 | 0.42 | 0.06 |
| 973.15~1023.15 | -0.02 | 0.06 |
| **EOL Condition** | | |
| Temperature Range [K] | MTC [pcm/K] | Uncertainty [pcm/K] |
| 823.15~873.15 | 1.65 | 0.05 |
| 873.15~923.15 | 1.10 | 0.05 |
| 923.15~973.15 | 0.64 | 0.05 |
| 973.15~1023.15 | 0.10 | 0.05 |

decrease compared to the BOL condition, which corresponds to the calculated result.

However, the MTC values evaluated at the EOL condition become larger compared to the BOL condition for the case of having burnable absorbers, which is caused by the production of $^{7}$Li and $^{4}$He from transmutation of boron that effectively slows down neutron through collision. Whereupon, both the neutron spectrum and calculated MTC values at the EOL condition are similar regardless of the presence of BAs.

The proposed BA concepts were also applied for an enlarged CMSR design having an extended lifetime of 20 years. Table 5 summarizes the modified CMSR design and BA specifications, where only the inactive volume has been increased to extend the lifetime, i.e., the active core configuration is identical to the original design discussed in Section 2. The thickness of SS316 cladding has been doubled to 300 μm, and the depletion calculation result is illustrated in Fig. 6, where excess reactivity is controlled below about 1,100 pcm.

Table 5. Enlarged CMSR and BA designs

| Type | Geometry | Location |
|---|---|---|
| Inactive Core | $r_{OUTER}$ = 167.32 cm | - |
| Rod-in | $r_{ROD}$ = 0.530 cm | Inner Core |
| Rod-out | $r_{ROD}$ = 0.479 cm | Outer Core |
| Plate-in | Width = 0.04 cm<br>Length = 1.960 cm | Inner Core |

## 5. Summary and Conclusions

In this study, burnable absorber concepts for Seaborg Technologies' compact molten salt reactor (CMSR) have been proposed and its impact on various neutronics features was investigated. Through the combination of rod and plate type $B_4C$-based burnable absorbers, it was demonstrated that a similar operation period could be met whilst sustaining the excess reactivity swing below 1,000 pcm. Such a feature alleviates the burden of controlling the excess reactivity using soluble-boron-like methods, which hampers the inherent safety of the system by increasing the MTC values.

To scrutinize the repercussion of including the BAs in the reactor core, radial flux profiles at BOL, MOL, and EOL conditions were compared. It was found that the inclusion of BAs rather reduces the localized peaking, which implies no additional safety concern for power peaking is introduced. In addition, the presence of BAs reduces the MTC values at BOL condition based on spectrum hardening.

Through an extension of inactive core volume, the lifetime of CMSR was enhanced to 20 yrs, and the same BA concepts have been exploited. The calculated excess reactivity was below 1,100 pcm, which plainly attests to the general applicability of BA concepts for reactivity control in CMSR. Further material compatibility-related research will be performed.

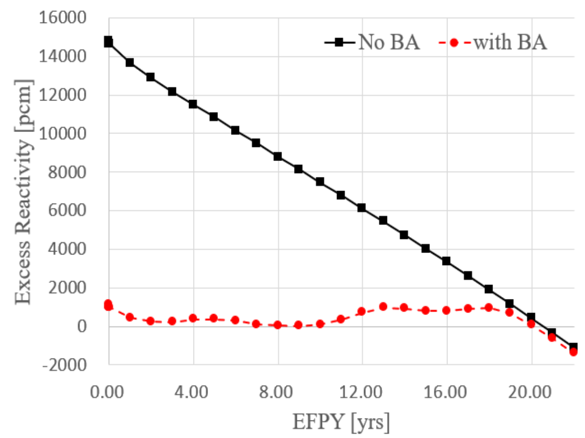


Figure 6. Implementation of BAs for an enlarged CMSR design (20yrs lifetime)

## ACKNOWLEDGEMENTS

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